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A Summary on Cutting Edge Advancements in Sterilization and Cleaning Technologies in Medical, Food, and Drug Industries, and Its Applicability to Spacecraft Hardware

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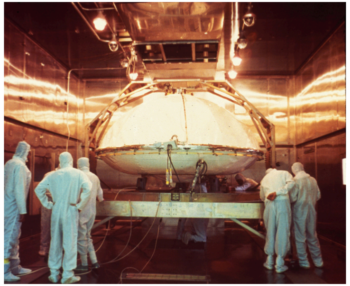
Introduction

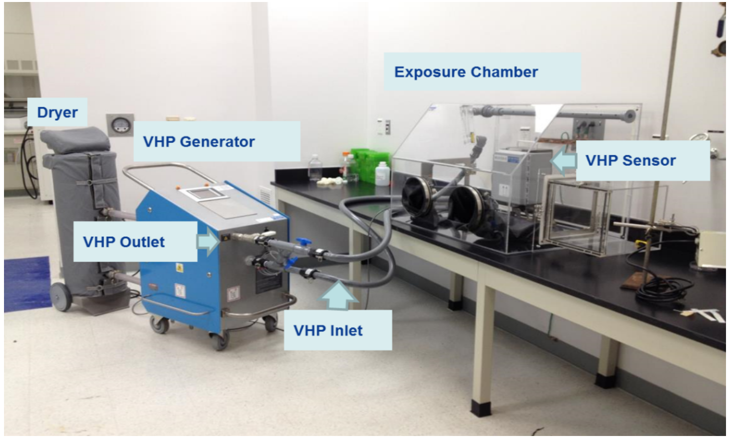
- Issued primarily by COSPAR (the Committee On SPAce Research), international planetary protection policies mandate that all spacecraft hardware in contact with extraterrestrial environments "*of chemical evolution and/or origin of life interest and for which scientific opinion provides a significant chance of contamination which could compromise future investigations*" * be sterilized
  - These policies seek to limit the (forward) biological contamination of the target body by terrestrial microorganisms on the spacecraft, so that future missions to the target body will provide accurate and reliable scientific results
  - Also these policies seek to prevent the (backward) biological contamination of the Earth by a sample returned from the target body
- Bioburden reduction is an integral part of current space missions and its importance will magnify as sterilization requirements become more stringent in the future
- Since life detection and sample return procedures require a sterile in situ environment (to protect scientific results), subsystems and instruments which will be in contact with extraterrestrial matter must be sterilized

* G. Kminek and J. D. Rummel, "COSPAR ' s Planetary Protection Policy," no. since 1964, 2014.

Introduction

- Since the first Viking mission, Heat Microbial Reduction (HMR) has served as a well-understood common practice for sterilization
- More recently, NASA and ESA have approved a standard protocol for Vapor Hydrogen Peroxide (VHP) sterilization to address some of the drawbacks of HMR by lowering operating costs and decreasing schedule impacts
  - However, even VHP has certain pitfalls that do not make it an all-encompassing sterilization modality for spacecraft (S/C) hardware (H/W)





Introduction

- Therefore, the team investigated the state-of-the-art sterilization and cleaning techniques used in other fields, such as in the medical, food, and drug industries, for application to flight hardware
  - Major techniques covered include Cold Atmospheric Plasma, Electron Beam Irradiation, and Gamma Irradiation
  - Some techniques have proven to be good candidates for adaptation for future NASA S/C missions, such as gamma irradiation (γ rad), can broaden the scope of NASA-approved protocols and expand the currently limited toolkit
- Cleaning is also an important aspect of bioburden reduction; despite the best sterilization technologies, dead microbes can interfere with and potentially invalidate the results of biosignature models of relevant celestial bodies
  - Therefore, cleaning techniques, such as carbon dioxide snow, can significantly contribute to the bioburden reduction process

Currently Approved Sterilization Protocols

- Heat Microbial Reduction is an environmentally friendly technique that uses high heat for an extended period of time to sterilize both surfaces and bulk materials (by penetration) of an object
  - Primary issues with HMR include materials compatibility, cost, and schedule impact due to the length of chamber time – particularly the high operating costs of high heat and long duration of time baking the materials
  - If testing identifies a need to rework previously HMR-processed H/W, then a repeat of HMR process following rework can cause unacceptable schedule slip
- Therefore, a new method for sterilization, VHP, was developed to increase efficiency, and address some of the pitfalls of HMR
  - VHP is lower cost, ideal for heat-sensitive parts, more efficient processing time
  - However, VHP is only able to sterilize surfaces
- As a result, it is necessary to investigate additional sterilization and cleaning techniques in order to expand the scope of hardware treatments

Other Sterilization Techniques Investigated

- Physical Methods:
  - Autoclave Steam Sterilization
  - Pressure Vapor Sterilization
- Chemical Methods:
  - Ethylene Oxide Sterilization (ETO)
  - Formaldehyde Sterilization
  - Chlorine Dioxide Gas Sterilization
  - Peracetic Acid Sterilization
  - "Cold Atmospheric Plasma" Sterilization (CAP)
    - Dielectric barrier discharge (DBD)
    - Atmospheric pressure plasma Jet (APPj)
    - Surface Micro-Discharge (SMD)

Other Sterilization Techniques Investigated

- Irradiation Methods:
  - Ultraviolet (UV) Sterilization
  - High energy X-ray Sterilization
  - Electron Beam (E-beam) Sterilization
  - Gamma Ray Sterilization

Cleaning Techniques Investigated

- Single-Wafer Spin Cleaning with Repetitive Use of Ozonated Water and Dilute Hydrogen Fluoride (SCROD)
- Low-Pressure Chamber Vapor Cleaning
- Carbon Dioxide Methods:
  - Super-critical CO_2
  - CO_2 snow
  - Liquid CO_2
  - Dry ice pallets
- Other Cleaning Techniques:
  - Multi-Tank Immersion RCA Cleaning
  - Cryogenic Aerosol-based Cleaning
  - Laser Cleaning

Conclusions
Techniques with NASA-Approved Protocols

Technique	Advantages	Disadvantages
HMR	Repeatability	Time Consuming
	Volumetric Reduction	High Temperature
	Non-Corrosive	Slow Rate of Heating Penetration
	Non-Toxic	Incompatibility with some Plastics
		Facility cost
VHP	Cost	Surface Microbial reduction
	Time	Reactive with certain materials
	Repeatability	Pre-conditioning
	Low Temperature	

Conclusions
Techniques without a NASA-Approved Protocol

- Some techniques were definitely not compatible with S/C H/W, the following techniques were investigated in greater depth:

Technique	Advantages	Advantages & Disadvantages Dependent on Technique	Disadvantages
CAP	Low Temperature	Time	Cost
	Multiple Sporicidal Agents	Sporicidal Effect	Toxic
		Geometry	

Conclusions
Techniques without a NASA-Approved Protocol

Technique	Advantages	Advantages & Disadvantages Dependent on Technique	Disadvantages
Gamma Irradiation	Volumetric		Facility cost
	Low Temperature		Radiation safety (for humans)
	Time		Polymers & glasses can be affected
	Predictable and Repeatable		
	No Radiation Byproduct or Residual		
	No Further Process		

Conclusions
Techniques without a NASA-Approved Protocol

Technique	Advantages	Advantages & Disadvantages Dependent on Technique	Disadvantages
E-beam	Low exposure time		Facility Cost
	Sterilization of polymers		High dose necessary
	Ozone generation		
Carbon Dioxide	Low Temperature		Surface cleaning
	Time		Non-hydrocarbon group
	Not Toxic or Corrosive		
	Possibility to clean MEMS and CMOS		

JPL

Conclusions
Technique Chosen for Development

- The team chose gamma irradiation sterilization as the next technique to develop into a standard protocol for NASA

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